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GAS-TUNGSTEN-ARC-WELDING OF TITANIUM CONTAINERS FOR NUCLEAR FUEL WASTE DISPOSAL

Report No 87-15-K

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ABSTRACT

This report describes the results of an investigation into pulsed-current gas-tungsten-arc (P-GTA) welding for the final closure of titanium containers for nuclear fuel waste disposal. A suitable weld-joint design, weld-joint fit-up tolerance, and suitable welding conditions have been established for welding titanium in the 2G position (container vertical). It has been demonstrated that sound, simulated lid welds on a titanium pipe mock-up can be made consistently, using an optimized closure welding procedure. However, it has also been shown that with existing mechanized P-GTA welding equipment, the welding parameters and the torch position require continuous surveillance by the welding operator at the welding station to ensure welds of acceptable quality. The specifications of an automated P-GTA orbital welding system have been described. The system would possess capabilities for adaptive feedback control of welding parameters (i.e, torch path and process variables) according to weld-path variations and weld-joint geometry variations. With an automated P-GTA welding system, final closure welding could be carried out with minimal need for operator surveillance. Furthermore, the reliability and reproducibility of sound titanium closure welds would be improved with an automated welding system.

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EXECUTIVE SUMMARY

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Metallurgy Section
Metallurgical Research Department

As part of Ontario Hydro's technical assistance to the Canadian Nuclear Fuel Waste Management Program, the Welding Unit of the Metallurgical Research Department carried out an investigation into the feasibility of using pulsed-current gas-tungsten-arc (P-GTA) welding for the final closure of titanium containers for nuclear fuel waste disposal. The process was shown to be both feasible and promising for the final closure of titanium containers with wall thickness between 4 to 6.4 mm.

The effects of weld-joint design, gas shielding, weld-joint fit-up variations, and welding parameters (current, wire-feed rate, voltage, pulse rate, and pulse width) on the quality of the closure welds were determined through extensive welding trials. A welding database was established, which could be used to optimize a P-GTA closure-welding procedure. It was demonstrated that a sound, simulated lid weld in a titanium container mock-up could be made consistently when the recommended weld-joint design and an optimized mechanized P-GTA welding procedure were used. It was noted, however, that with mechanized P-GTA welding continuous surveillance by the welding operator at the welding station would be required to ensure sound quality in the closure welds. This is not feasible for the production of final closure welds in nuclear fuel waste containers. The development of an automated orbital welding system with the capability of adaptive feedback control of the weld path and welding parameters is also described. Such a system would eliminate the need for an operator at the welding station and improve the likelihood of consistently producing sound closure welds.

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GAS-TUNGSTEN-ARC WELDING OF TITANIUM CONTAINERS FOR NUCLEAR FUEL WASTE DISPOSAL

1.0 INTRODUCTION

1.1 Background

As part of Ontario Hydro's technical assistance to the Canadian Nuclear Fuel Waste Management Program, the Welding Unit of the Metallurgical Research Department is developing suitable welding procedures for the final closure of nuclear fuel waste disposal containers.

Titanium is one of the candidate materials being considered as suitable for use as a corrosion-resistant shell material/1,2/. This report describes progress to date in the development of pulsed-current gas-tungsten-arc (P-GTA) welding procedures for the final closure of titanium containers (wall thickness between 4.0 to 6.4 mm). Based on the findings of this investigation, recommendations are made on procedural and equipment requirements for container closure welding.

1.2 Specific Requirements for Closure Welding of Titanium Containers

One of the thin-walled titanium, supported-shell container designs being considered for nuclear fuel waste disposal is shown in Figure 1. The joint design for the final closure illustrated in the figure uses the resistance-heated diffusion bonding process, which is an alternative final closure welding process under consideration /3/. A different top lid and weld-joint design would be required for a closure designed for P-GTA welding.

Because the used fuel is highly radioactive, all handling, final closure welding and inspection must be done remotely. Furthermore, due to concerns related to tilting an unsealed container containing used fuel, it is preferable to perform the final closure weld in the 2G position (container vertical). In this study, all welding trials were carried out in this welding position.

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Previous work /4/ showed that titanium reacts readily with, and becomes embrittled by available air contaminants such as oxygen and nitrogen in the weld zone. For the titanium container designs under consideration, it is very difficult, if not impossible, to provide backing gas coverage for the weld root. Therefore, it is desirable to develop a GTA welding procedure and weld joint design that can produce full penetration titanium closure welds without the use of a backing gas shield device. The final closure weld should be free of any weld defects such as lack of fusion, cracking, gas porosity, excessive weld reinforcement, undercut and concavity.

The container shells would likely be made from titanium plates (i.e. by cold forming and welding operations) and it is certain that the shells would contain some out-of-roundness. The final closure welding procedure must, therefore, be able to accommodate a certain degree of high/low misfit caused by the out-of-roundness of the container shell.

2.0 EXPERIMENTATION

2.1 Materials

Commercially pure Grades 2 and 12 titanium are being considered as candidate shell materials. The chemical composition of the titanium base and filler metals used in the present study are shown in Table 1. Preliminary studies at OHRD showed that these two grades of titanium display similar welding characteristics. Grade 2 titanium was selected for the present work. A series of single V-groove butt joints of Grade 2 titanium were made using both Grade 1 and Grade 2 titanium filler wire. The test results showed no significant difference in welding characteristics and mechanical properties (see Table 2). Grade 2 filler wire was selected for welding Grade 2 titanium base metal in the present study. The welding procedure chosen for Grade 2 titanium was also used to fabricate Grade 12 welded samples with Grade 12 filler wire for the evaluation of mechanical properties.

2.2 Welding Trials

In Phase One of the present work, P-GTA welding studies were carried out on commercially pure grade 2 titanium plates, 4.0 and 6.4 mm thick, using a Dimetrics Gold Track II Pipe Welding System. Test plates 38 mm in width and 102 mm in length were machined, ground, and cleaned in acetone. Single-vee-groove butt joints were made in the 2G welding position using the weld assembly shown in Figure 2. Excellent gas shielding of the hot weld metal and heat-affected zone was achieved with a specially designed, trailing gas shield device. Backing plates of matching material composition were used in all welding trials to simulate the integral backing that would be provided by the top lid. No backing gas shield was used. Over one hundred and fifty weld samples were made using a wide range of welding parameters and weld-joint geometries. A suitable operating range of welding parameters, and an appropriate weld joint geometry were determined for joints with different fit-up conditions.

In Phase Two, two simulated lid welds were made in a titanium pipe mock-up, using an optimized welding procedure developed for welding 6.4-mm thick titanium. The weld assembly set-up is shown in Figure 3.

Metallurgical examination and hardness and tensile tests were performed on selected samples of welded plate and selected cross sections of the simulated lid welds. Ultrasonic inspection studies were performed on one of the lid welds.

3.0 EXPERIMENTAL RESULTS

3.1 Weld-Joint Designs for the Closure of Titanium Containers

The weld-joint design recommended for use in the final closure of titanium containers consists of a single V-groove that uses the top lid as an integral backing (see Figure 4). In the present work, single V-groove butt joints with backing support were made using various combinations of root gap, groove angle, and high/low misfit. Based on the test results, different combinations of groove angle and root opening have been recommended for titanium containers of different thicknesses (see Table 3). Schematic diagrams of weld defects caused by an improper weld joint geometry are shown in Figure 5.

It was shown that weld joints containing no root gap were prone to weld defects such as root cavities and inadequate root fusion or penetration into the backing plate (see Figure 5). In the presence of an integral backing, a relatively large root opening could be incorporated into the present joint design without causing root burn-through. Root openings in the range of 3 to 4 mm were required to bridge a weld-joint misfit of up to 2 mm.

A suitable included groove angle for each container wall thickness under consideration is shown in Table 3. The use of a groove angle smaller than the specified range would likely cause lack-of-fusion defects and irregular melting of the weld-joint shoulder (see Figure 5). The use of a groove angle larger than the specified range would require an excessive amount of weld metal to fill the joint. To reduce weld-pool sag, the width of the weld shoulder had to be kept as small as allowable. The present work showed that the shoulder width should be kept within 9 to 11 mm.

3.2 Closure-Welding Conditions

The test results indicated that for P-GTA closure welding of titanium containers, the welding current, wire feed rate, arc voltage, pulse width, and pulse rate all directly affect weld quality and must be carefully controlled to obtain optimum weld quality and mechanical properties.

Recommended welding parameters for the groove welding of titanium in the 2G welding position are shown in Table 4. Common weld defects in titanium groove welds and their causes are shown in Figure 5.

3.2.1 Welding Current and Wire Feed Rate

Compared to all other weld parameters tested in the present study, welding current and wire-feed rate appear to be the most critical parameters affecting weld quality. Pulsed current, together with synchronized pulsed wire-feed rate, were used in the welding trials to obtain optimum weld-puddle control and weld quality. The welding current was pulsed between peak (primary) and background current levels. For groove welding of titanium, relatively high primary current levels were required to obtain satisfactory weld-pool wetting and adequate fusion. In the 2G welding position, it was desirable to keep the average current level and the heat input as low as possible to reduce any risk of weld-pool sag and air contamination of the weld metal/4/. Low average-current levels were obtained by using low background-current levels. The wire-feed rate was also pulsed between primary and background speed settings.

A proper relationship between the welding current and wire-feed rate was also essential to acquire optimum weld quality. In Figure 6, the operating range of wire-feed rate for welding current levels in the range of 40 to 200 amperes is enclosed by the boundary lines LMAX and LMIN. The boundary line LMAX is called the maximum wire-feed rate line, which defines the maximum wire-feed rate for a given welding current, above which wire stubbing and tungsten-to-work contact might occur. The boundary line LMIN is called the minimum wire-feed rate line, which is defined as the minimum wire-feed rate for a given welding current, below which wire balling might occur. For a particular current level, a proper wire-feed rate could be selected within these boundary lines.

In addition to the need for a proper relationship between welding current and wire-feed rate, proper feed of the filler wire into the weld puddle is critical to insure a smooth solid-to-liquid transition and a smooth filler metal transfer (see Figure 7). It was shown that smooth weld-metal deposition and thus, stable welding conditions, were essential to acquire optimum weld quality. For a particular current level, a proper wire-feed rate could be selected within the boundary lines shown in Figure 6. Periodic adjustment of the wire-feed angle by the operator during welding was necessary to insure proper wire entry and, thus, weld quality.

For the weld-joint designs recommended for the final closure of titanium containers (see Table 3), suitable ranges of welding current and wire-feed rate for the root pass, fill passes and capping passes are shown in Table 4 and Figure 6.

For any particular weld-joint geometry recommended in Table 3, the optimum primary current level and wire-feed rate for the root pass and fill passes can be selected from within the boundaries of Box A, see Figure 6. Generally, relatively high primary welding current levels in the range of 160 to 180 amperes were required to ensure satisfactory weld wetting and fusion. Inadequate primary current and wire-feed rate levels might cause lack-of-fusion defects (see Figure 5). Excessive current and wire-feed rate would

cause excessive melting of the shoulder of the weld joint and poor weld-pool control. To maintain stable welding conditions and a relatively low heat input, the background current and wire-feed rate could be selected from within Box C of Figure 6.

For the weld-capping passes, the weld pool had a greater tendency to sag since there was little or no side wall to contain the molten weld metal. In comparison to the root pass and fill passes, much lower welding current and wire-feed rate levels are recommended for the capping passes to acquire an optimum weld surface profile (boxes B and D of Figure 6).

3.2.2 Arc Voltage

The optimum arc voltage appeared to be in the range of 9.0 to 10.0 volts. Lower arc voltage, and thus shorter arc length, promoted tungsten electrode-to-work contact. Higher arc voltage and arc length caused unstable arc behavior, and adversely affected wire feeding.

Two voltage control modes were investigated in the present work. In one mode, the voltage was sampled continuously. To weld titanium in the 2G position, a large difference between the primary and background current levels was preferred to obtain optimum weld-pool control. When the continuous sampling mode was used, the control tended to vary the electrode-to-work distance to maintain constant arc voltage and this caused electrode-to-work contact and erratic welding arc behavior. In the other mode, the arc voltage was sampled only when the current was at primary level and the control did not readjust the electrode spacing to compensate for current changes during the background-current time. With the use of this voltage sampling mode, it was found that stable arc conditions could be achieved even when high welding current and low background current levels were used.

3.2.3 Welding Travel Speed/Pulse Width/Pulse Rate

In this study, the pulse width was defined as the ratio between the time the current pulsed at the primary current level and the total time the current pulsed at the primary current level plus the background level. The pulse rate was defined as the number of complete pulses per second.

It appeared that a proper relationship among the pulse width, the pulse rate and the welding speed was paramount for weld-bead spacing and weld puddle-control. For welding speeds between 1.06 to 1.27 mm/sec (i.e. 2.5 to 3 inch/minute), it was shown that a pulse width of 50% and a pulse rate of 1 pps (pulse per second) appeared to be optimum for our requirements. With this welding speed range and pulse conditions, it was found that sound groove welds could be made under most weld-joint fit-up and joint geometry conditions, using a wide range of welding current and wire-feed rates. This greatly simplified the control scheme for adjusting welding parameters under varying weld-joint conditions. The use of other pulse parameters (e.g. 70% pulse

width) tended to reduce the usable range of welding current and wire feed rate. For the relatively high level of primary current required, pulse widths greater than 50% increased the heating time and reduced the cooling time between weld pulses. The excessive heat caused the weld pool to sag under its own weight. In this case, the weld current had to be reduced which would, in turn, cause lack-of-fusion defects.

3.3 Procedural Optimization for Closure Welding of 6.4-mm Thick Titanium Containers

3.3.1 Selection of Groove Angle

Based on the recommendations shown in Table 3, a single V-groove butt joint with a relatively small, 45° included groove angle was selected, as illustrated in Figure 3. The weld-joint design selected has a 4-mm wide root gap.

3.3.2 Optimization of the Welding Procedure

It was found that the P-GTA process parameters for the final closure welding in the 2G welding position could be divided into two groups. Group 1 consisted of welding current and wire-feed rate. Group 2 consisted of process variables such as arc voltage, welding travel speed, pulse rate and pulse width. Group 1 parameters were found to be more critical for controlling the weld quality. It would appear that optimization of the final closure welding procedure could be carried out by selecting proper settings for the Group 1 parameters within the recommended ranges as defined in Figure 6 and Table 4, while Group 2 parameters were maintained at the specified levels shown in Table 4.

A number of weld tests were carried out to determine an optimum welding procedure and weld-bead deposition sequence for welding 6.4-mm thick titanium containers. Different combinations of welding current and wire-feed rate were used in these tests for the root pass, fill passes and capping passes. Appropriate current and wire feed rates were selected according to the recommendations of Figure 6. The details of these tests are shown in Table 5. The test results are summarized as follows:

- the welding parameters of Test 3 appeared to produce the best weld quality and an optimum weld-bead deposition sequence (i.e.,one root pass, two fill passes and two capping passes);

- sound titanium welds displaying good surface profiles could be made using Test 3 parameters under varying weld-joint fit-up conditions (see Figure 8); a maximum misfit of 2 mm could be accommodated using Test 3 parameters;

- two fill passes were preferred to one fill pass to obtain optimum weld-pool control; a one fill-pass procedure (e.g., Test 2 parameters) required an excessively high wire-feed rate (see Table 5 and Figure 6)

and tended to cause inadequate fusion between the weld beads and excessive melting of the upper shoulder of the weld joint;

- two capping passes employing a low welding current and low wire-feed rate were most desirable for insuring an optimum weld-bead surface profile and preventing weld-pool sag in the 2G welding position; a one-capping pass welding procedure (e.g., Test 1 parameters) required very accurate torch-position control to avoid weld defects such as undercutting;

- Test 4 parameters produced acceptable welds, but required an excessive number of weld passes;

- proper positioning of the welding torch was required to obtain an optimum weld-bead profile in each weld pass (see Figure 9).

3.4 Closure Welding of Titanium Pipe Mock Up

3.4.1 Fabrication of Titanium Pipe and Top Lid

A Grade 2 titanium pipe was fabricated for OHRD by Titanium Limited in St. Laurent, Quebec. The pipe, 13 mm thick, 220 mm in diameter, and 300 mm long was rolled and joined with a longitudinal GTA seam weld. At receipt, the outside and inside diameters of the pipe displayed about 1 to 2-mm out-of-roundness. Both the inside and outside surfaces of the pipe ends were machined round. The wall thickness was reduced to 6.4 mm (1/4 inch). Two lids were machined as shown in Figure 3. These were inserted into either end of the pipe; the resultant cross section of the weld joint preparation is shown in Figure 3. The weld-joint preparation consisted of an integral backing, a 45° included angle 'V' groove and a 4-mm wide root gap. The joint preparation had excellent fit-up.

3.4.2 Closure Welding and Ultrasonic Inspection of Titanium Pipe Mock Up

Two simulated lid welds (1 and 2) were made in the 2G welding position. The weld assembly is shown in Figure 4a. During the welding procedure, the welding head rotated around the pipe mock-up on a circular track. Details of the procedures for tack welding, weld initiation, main weld and weld termination are shown in Table 6. The main weld was made using the welding parameters and weld-bead deposition sequence used in Test 3 (see Table 5).

To investigate the ultrasonic inspectability of the simulated lid weld, four defects were introduced intentionally into lid weld 1. A grease spot was placed in area A to induce porosity in the weld metal. In area B, the top lid was filed to introduce a misfit. In area C, lack of root fusion was achieved by manual GTA welding. In area D, electrode-to-work contact was induced to create a tungsten inclusion in the root pass.

For both lid welds, excellent weld metal wetting and fusion were observed during all weld passes. The surface-weld beads displayed no sign of air contamination (i.e., silver in color) and satisfactory weld bead profiles (see Figure 4a).

Ultrasonic inspection of lid weld 1 was used to detect all four intentional defects, using a normal beam scan from the top surface. In this case, the weld crown was not ground. Cross sections containing the defective areas were prepared for metallographic examination. However, no weld defects were found. Complete root fusion was achieved in area B, which contained a misfit of 1.5 mm. A typical cross section of lid weld 1 is shown in Figure 4b. The details of the ultrasonic inspection studies are described in a separate OHRD report/5/.

3.5 Evaluation of Microstructure and Mechanical Properties of Titanium-Based Metal and Welds

3.5.1 Grade 2 Titanium

Metallurgical examination was performed on cross-sections of representative Grade 2 titanium welded samples. The base metal contained equiaxed alpha grains and the weld metal contained relatively large serrated alpha grains (see Figure 10).

Vickers hardness tests were performed on sections of representative weld samples in plate material and on typical cross-sections of the titanium pipe mock-up. The results are shown in Table 7.

Although no backing-gas shield was used in the present work, the weld metal of all the Grade 2 titanium samples (including those that were welded under different misfit conditions) displayed acceptable weld hardness, i.e., they satisfied the standard of a maximum weld hardness increase of 30 Vickers points over the parent metal/4/. In fact, the hardness of the simulated lid weld was about 27 Vickers points lower than the hardness of the base metal.

Transverse tension tests were performed on representative weld samples. All samples tested displayed satisfactory tensile properties. The fracture surfaces of the tension samples were examined by scanning electron microscope; all fractures appeared to be ductile.

3.5.2 Grade 12 Titanium

Cross-sections of welded Grade 12 titanium samples were metallurgically examined. Base-metal and weld-metal microstructures are shown in Figure 11. In the base metal, angular particles were found in a continuous matrix of alpha grains; these particles were presumably a Ti Ni intermetallic phase. The weld metal contained fine acicular alpha grains.

Vickers hardness tests and transverse tension tests were performed on representative weld samples. The results are shown in Tables 7 and 2, respectively.

In the Grade 12 titanium welds, the hardness of the weld metal was about 40 Vickers points higher than that of the base metal which does not satisfy the maximum increase of 30 Vickers points specified for Grade 2 titanium welds. Visual examination of the welds showed no indications of weld-metal contamination. Transverse tension tests performed on the weld samples also showed satisfactory tensile strength and ductility. The high hardness of the weld metal was apparently caused by the fine acicular grain structure, rather than by air contamination of weld metal.

4.0 DISCUSSION

4.1 Feasibility Studies

The present work has demonstrated that P-GTA welding is both feasible and promising for the final closure of thin-wall supported-shell titanium containers for nuclear fuel waste disposal.

It was shown that sound titanium closure welds could be made easily and consistently in the 2G welding position (i.e., container in the vertical position) using the welding procedures and weld joint configurations as described in this study. Welds displaying acceptable hardness and tensile properties could be made without the use of a backing gas shield. This was achieved by using a well designed trailing gas shield device for surface shielding (see Figure 2) and a single V-groove weld-joint design with integral backing support. A relatively low average welding current during the root pass (and therefore a low heat input) also contributed to lowering the risk of weld-metal air contamination.

It is certain that the shell of a full-size container will contain some degree of out-of-roundness, resulting in weld-joint high/low mismatch. The present work has shown that good quality titanium welds can be made in the presence of a maximum mismatch of 2 mm. This was achieved by using a weld joint employing a relatively large root gap (in the range of 3 to 4 mm) and proper root-pass welding procedures. With the present joint design and integral backing, a large root gap could be used without inducing weld defects such as root burnthrough.

The present work has shown no significant difference in weldability between Grades 2 and 12 titanium. Therefore, the welding procedure developed could be used for containers fabricated from either material.

4.2 Ultrasonic Inspectability of the Closure Welds

It was shown that closure welds in Grade 2 titanium containers employing the suggested weld joint design were inspectable by ultrasonic techniques/5/. Both C- and B-scans were performed on the simulated lid weld using a normal beam from the top surface of the lid. Weld defects induced by the presence of grease, a tungsten inclusion, and poor weld-bead placement were readily detected. However, only extraneous signals were obtained in poor weld-joint fit-up areas, despite the fact that a sound weld was obtained in these areas. In order to distinguish poor fit-up areas from lack-of-fusion in the root pass, it would be necessary to perform a normal beam inspection from the side/5/. This would require the weld crown to be removed. Pre-matching heads and shells and proper fit-up techniques could be used to avoid significant mismatch in a production container at a used-fuel waste disposal centre.

Grade 12 titanium base and weld metal appeared to display different microstructures than that of Grade 2 titanium. The ultrasonic inspectability of Grade 12 titanium containers thus will require further investigation.

4.3 Closure Welding of Titanium Containers for Nuclear Fuel Waste Disposal

4.3.1 Mechanized GTA Welding

A database of suitable welding conditions has been established for the final closure of thin-wall nuclear fuel waste disposal containers using mechanized P-GTA welding. These conditions include: a) weld-joint design (groove angle and root gap); b) welding parameters (current, wire feed rate, arc voltage, pulse width and pulse rate); c) weld-joint fit-up tolerance; d) primary and trailing gas shielding. It was also shown that optimization of the closure welding procedure for a titanium container with a particular wall thickness could be easily accomplished using the welding data collected.

4.3.2 Automated GTA Welding

For mechanized GTA welding, it was found that continuous surveillance and adjustment of welding parameters (e.g., wire-feed angle and torch position along the weld groove) by the welding operator were required during final closure welding to ensure sound weld quality. This requirement is, of course, impossible to fulfill for the final closure weld of nuclear fuel waste containers.

A recent survey performed by the Welding Unit of the Metallurgical Research Department and AECL-SPEL/6/ indicated that with recent advances in welding and welding-related techniques and equipment, it would be technically feasible to develop an automated orbital GTA welding system with the following capabilities:

(a) automated guidance of the welding torch with adjustments as required according to weldpath variations;

(b) adaptive fill control by adjustment of the welding parameters according to weld-joint geometry and fit-up variations;

(c) remote TV viewing that would provide a human operator with visual feedback from the welding process.

An automated orbital GTA welding system possessing the above capabilities would be ideal for the final closure welding of titanium containers.

The Welding Unit of the Metallurgical Research Department is currently developing an automated orbital welding system for maintenance and in-situ repair welding of large diameter piping in Ontario Hydro/7/. A similar system could be used for the final closure welding of titanium nuclear fuel waste disposal containers. As illustrated in Figure 12, the conceptual automated orbital welding system would be composed of: 1) a sensor to measure key features of the joint; 2) a torch positioning system (i.e., welding head equipped with optical encoder); 3) transistorized power supplies (GTA and/or GMA); 4) a torch position controller to correct the position of the welding head; 5) a weld controller to adjust the welding variables on the basis of measurements of the joint features and dimensions; 6) a TV viewing system for remote viewing and monitoring of the welding process.

According to the preliminary work schedule/7/, the total time required for the automated orbital welding program is five years; preliminary work began in 1986. At completion, the automated orbital welding system would be adaptable to both GTA and GMA welding. The automated welding system could be used for the following nuclear waste disposal related applications:

a) final closure welding of thin-walled titanium containers using GTA welding.

b) final closure welding of thin-walled Inconel 625 containers using GTA welding/8/.

c) final closure welding of thick-walled copper containers using GMA welding.

d) final closure welding of thick-walled iron-based containers using either GTA or GMA welding.

5.0 CONCLUSIONS

5.1 It is feasible to perform the final closure of thin-walled titanium containers using P-GTA welding. It has been demonstrated that final closure welds of consistently acceptable weld quality and satisfactory mechanical properties can be made in the 2G welding position if the weld joint design, gas shielding devices and welding parameters recommended in this study are used.

5.2 The most suitable weld-joint preparation for the final closure weld is a single V-groove weld preparation with the top lid acting as an integral backing support. Guidelines have been established for the selection of a suitable groove angle and root gap width for containers with wall thicknesses between 4 to 6.4 mm.

5.3 Much has been learned from the present work about procedural and equipment requirements for the final closure welding of titanium containers by P-GTA welding. A welding database has been established, which can be used for the optimization of welding parameters for the final closure welding operation. We have demonstrated that weld joints displaying misfits of up to 2 mm can be welded successfully.

5.4 We have demonstrated that titanium welds displaying satisfactory mechanical properties can be made without the use of backing gas shielding. Grades 2 and 12 titanium display similar weldability, and welding procedures developed for Grade 2 titanium can be applied to Grade 12.

5.5 The present closure-weld joint appears to be inspectable by ultrasonic techniques. We have demonstrated that weld defects introduced by the presence of grease, a tungsten inclusion and poor weld placement can be readily detected.

5.6 We have shown that although mechanized P-GTA welding can be used for the final closure-welding operation, the present technique requires continuous operator surveillance at the welding station (i.e., to adjust the welding torch position along the groove and the wire entry). Development work on an advanced automated orbital welding system is progressing at OHRD. If successful, the need for operator surveillance at the welding scene can be eliminated, and the potential for introducing weld defects by imprecise manual adjustment would be minimized.

5.7 The weld-joint design and welding procedure developed in the present work can also be used for pre-assembly of the bottom lid to the shell.

ACKNOWLEDGEMENTS

The authors wish to express their thanks to Ms. S. Sandloehken of the Metallurgy Section for her SEM fractography, and to Dr. M. Moles and Mr. A. Allen of the Non-Destructive and Fracture Evaluation Section for performing the ultrasonic inspection studies. The editorial contributions of Mr. M.J. Tinkler of the Metallurgy Section and Mr. J.L. Crosthwaite of Atomic Energy of Canada Limited are also acknowledged.

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2. D.J. Cameron, "Fuel Isolation Research for the Canadian Nuclear Fuel Management Program," Atomic Energy of Canada Limited Report, AECL-6834 (1982).

3. P.Y.Y. Maak,"Resistance/Diffusion Bonding of Titanium Rings," Ontario Hydro Research Division Report 85-126-K, 1985.

4. P.Y.Y. Maak,"The Effect of Air Contamination in the Argon Shielding Gas on the Mechanical Properties of Titanium Gas-Tungsten-Arc Welds," Atomic Energy of Canada Limited Technical Record TR-282, 1984.

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7. P.Y.Y. Maak and M.J. Tinkler, " Proposal for the Development of Advanced Pipe Welding in Ontario Hydro," Ontario Hydro Research Division Report 86-308-H, 1986.

8. J.G. Galloway, "Gas-Tungsten-Arc Welding of Inconel 625 for Irradiated Nuclear Fuel Waste Disposal Containers", Ontario Hydro Division Report 86-147-K, 1986.

TABLE 1 - CHEMICAL REQUIREMENTS OF THE TITANIUM MATERIALS

	Composition %							
	N max	C max	H max	Fe max	O max	Mo	Ni	Ti
Ti Grade 2 plate	0.03	0.10	0.015	0.3	0.25	-	-	remainder
Ti Grade 12 plate	0.03	0.08	0.015	0.3	0.25	0.2-0.4	0.6-0.9	remainder
ER Ti-1	0.012	0.03	0.005	0.10	0.10	-	-	remainder
ER Ti-2	0.020	0.05	0.008	0.20	0.10	-	-	remainder
ER Ti-12	0.03	0.10	0.015	0.3	0.25	0.3	0.8	remainder

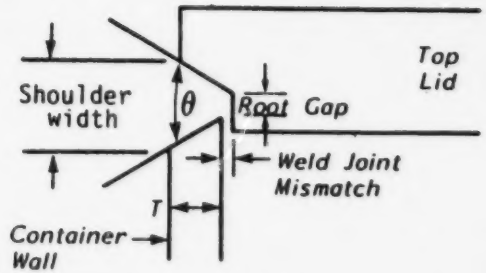
TABLE 2 - TENSILE PROPERTIES OF TITANIUM WELDS*

Base Metal	Filler Wire	UTS* MPa	Remarks
Grade 2	Grade 1	433	Ductile W/M failure
Grade 2	Grade 2	425	Ductile W/M failure
Grade 12	Grade 12	558	Ductile B/M failure
ASTM Specification Grade 2 Titanium Plate		345 minimum	
Grade 12 Titanium Plate		483 minimum	

*Average of data from two tension tests results

TABLE 3

RECOMMENDED WELD JOINT GEOMETRY FOR THE FINAL CLOSURE OF TITANIUM CONTAINERS



	CONTAINER WALL THICKNESS (T) mm	ROOT GAP mm	INCLUDED GROOVE ANGLE (θ) DEGREES	SHOULDER WIDTH mm	JOINT CROSS SECTION AREA mm^2	COMMENTS
*	6.4	4	45°	9.3	42.6	Recommended
	6.4	3	45°	8.3	36.2	Shoulder width too narrow
	6.4	4	60°	11.4	49.3	Shoulder width too wide, excessive joint volume
*	6.4	3	60°	10.4	42.9	Recommended
	6.4	3	75°	12.8	50.6	Shoulder width too wide, excessive joint volume
	5	4	45°	8.1	30.3	Shoulder width too narrow
	5	3	45°	7.1	25.3	Shoulder width too narrow
*	5	4	60°	9.8	34.5	Recommended
*	5	3	60°	8.8	29.5	Recommended
	5	4	75°	11.7	39.3	Shoulder width too wide, excessive joint volume
*	5	3	75°	10.7	34.25	Recommended
	4	4	45°	7.3	22.6	Shoulder width too narrow
	4	3	45°	6.3	18.6	Shoulder width too narrow
*	4	4	60°	8.6	25.2	Recommended
	4	3	60°	7.6	21.2	Shoulder width too narrow
*	4	4	75°	10.1	24.2	Recommended
*	4	3	75°	9.1	28.2	Recommended

* Recommended Weld Joint Geometry

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TABLE 4 - RECOMMENDED RANGE OF WELDING PARAMETERS FOR WELDING TITANIUM IN THE 2G WELDING POSITION

Welding Parameters	Tested Range	Recommended Range	Weld Passes	Remarks
Primary Current	100-200	160-185A	Root & Fill	To ensure sound weld bead wetting and fusion.
		115-135	Capping	To ensure optimum weld pool control.
Back-ground Current	45-110 45-60A	75-100A Capping	Root & Fill	To keep a low average heat input and optimum weld pool control.
Primary Wire Feed Rate(WFR)	3.11.4	4.7-8.5	Root & Fill	A proper relationship between the WFR & the welding current level is required. Improper WFR may cause tungsten electrode-to-work contact, filler wire stubbing & an irregular weld bead deposit (see Figure 7).
		3.4-6.4	Capping	
Back-ground Wire Feed Rate	1.7-5.5	2.3-5.1	Root & Fill	
		1.5-3.6 mm/sec	Capping	
Arc Voltage	8.5-10.5 V	9-10 V	All	Low arc voltage may cause tungsten electrode to contact work. Excessive arc voltage will cause an unstable and erratic arc.
Pulse Width	30,50,70%	50%		For a wide range of welding curr- & wire feed rate, optimum weld pool control can be obtained by using a pulse width of 50%, a pulse rate of 1 pps & welding speed range from 1.1 to 1.27 mm/sec.
Pulse Rate	0.5,1,2 pps	1 pps		
Travel Speed	0.85-1.7 mm/sec	1.10-1.27 mm/sec		
Tungsten Tip Angle (included	13-60°	24-30°		

TABLE 5

OPTIMIZATION OF WELD BEAD PLACEMENT SEQUENCE AND WELDING PROCEDURE FOR WELDING 6.4-mm-THICK TITANIUM IN THE 2G WELDING POSITION

Weld Joint = 45°; 4 mm Root Gap
Voltage = 9.5 Volt
Pulse Parameter = 1 pps 50% Pulse Width
Welding Speed = 1.0 mm/sec (2.5 in/min)

Bead Placement Sequence	WELD PASSES	PRIMARY CURRENT A	BACKGROUND CURRENT A	PRIMARY WIRE FEED RATE mm/sec (in/min)	BACKGROUND WIRE FEED RATE (in/min)
①	Root (R1)	180	100	7.6 (18)	3.8 (9)
	Fill (F1&F2)	180	100	7.6 (18)	3.8 (9)
	Capping (C1)	180	100	7.6 (18)	3.8 (9)
②	Root (R1)	180	100	7.6 (18)	3.8 (9)
	Fill (F1)	180	100	11.4 (27)	5.5 (13)
	Capping (C1&C2)	130	75	5.5 (13)	3.0 (7)
③	Root (R1)	180	80	5.5 (13)	3.0 (7)
	Fill (F1&F2)	180	80	6.8 (16)	3.8 (9)
	Capping (C1&C2)	130	50	4.7 (11)	2.1 (5)
④	Root (R1)	160	60	5.5 (13)	3.0 (7)
	Fill (F1&F2)	160	60	4.7 (11)	3.0 (7)
	Fill (F3&F4)	130	50	4.7 (11)	2.1 (5)
	Capping (C1&C2)	130	50	4.7 (11)	2.1 (5)

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TABLE 6 - OPTIMIZED WELDING PROCEDURE FOR THE FINAL CLOSURE OF 6.4 MM THICK TITANIUM CONTAINERS

GENERAL WELDING CONDITIONS

Gas cup size: 12 mm dia; pulse rate: 1 pps; pulse width: 50%;
welding carriage travel: 1.70 mm/sec or 4 in/min(continuous)
AVC: 9.5 volts , sampling during the high pulse current
2.4 mm diameter tungsten electrode: tip included angle- 24 degree
tip diameter - 0.8 mm
Primary gas flow rate through the gas cup: 12 l/min (25 cfh)
Secondary gas flow rate through the trailing gas shield: 33 l/min
(70 cfh)

WELD INITIATION PROCEDURES

- switch on primary and secondary argon shielding gas and prepurge for one minute;
- upslope current in 2 seconds to welding current levels of the main weld;
- activate AVC control and initiate welding carriage travel after 2 seconds;
- initiate wire feed after 1 second;

MAIN WELDING PROCEDURES

Root Pass Welding: I(p) at 180 A , I(b) at 80 A
WFR(p) at 12.7 mm/s, WFR(b) at 6.4 mm/s

Fill Pass Welding: I(p) at 180 A, I(b) at 80 A
WFR(p) at 14.8 mm/s, WFR(b) at 8.5 mm/s

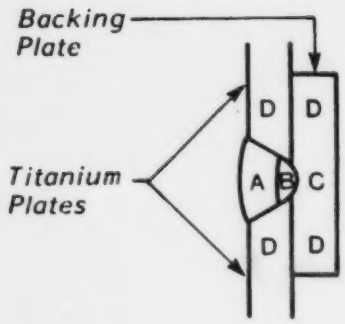
Capping Pass Welding: I(p) at 130 A, I(b) at 50 A
WFR(p) at 10.6 mm/s, WFR(b) at 4.2 mm/s

WELD TERMINATION PROCEDURES

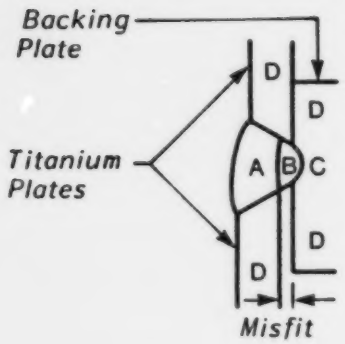
- current down slope over 30 seconds;
- terminate wire feed after 2 seconds;
- deactivate AVC control after 10 seconds;
- terminate welding carriage travel after 30 seconds;
- stop shielding gas flows after 60 seconds;

TABLE 7

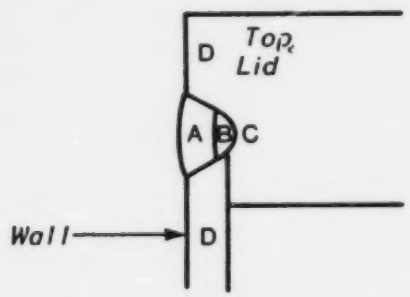
HARDNESS TEST RESULTS
AVERAGE HARDNESS DATA (1)



Base Metal	A	B	C	D
Grade 2	137	131	155	155
Grade 12	208	206	199	165



Grade 2 (1 mm Misfit)	151	127	156	155
Grade 2 (2 mm Misfit)	150	155	178	155



Grade 2	129	127	155	155

(1) - Vickers Hardness Test (Load - 2.5 kg)
A - Weld Bead Hardness (Fill and Capping Passes)
B - Weld Bead Hardness (Root Pass)
C - Heat-Affected Zone Hardness (Adjacent to the Root Pass)
D - Base Metal Hardness

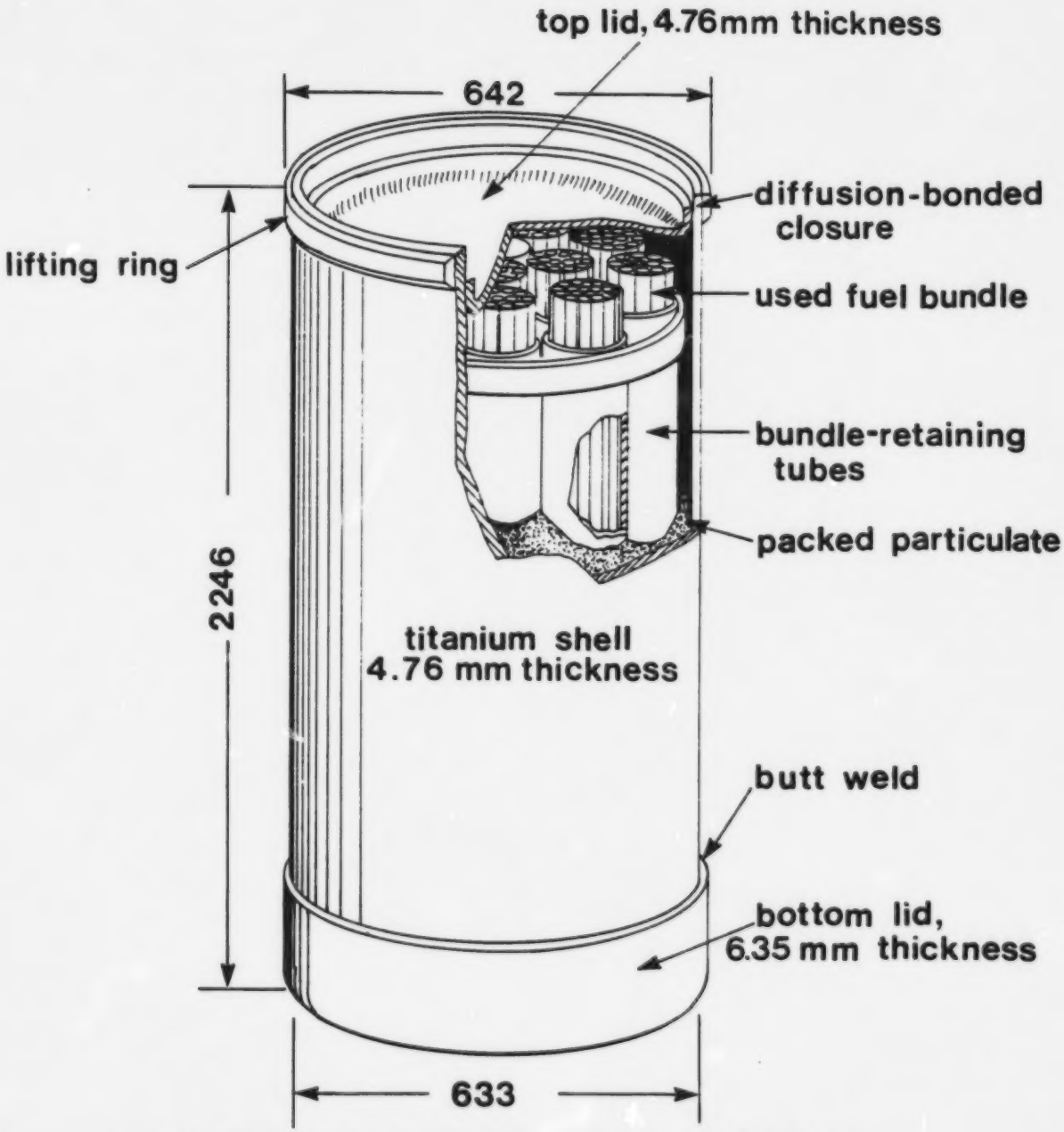


FIGURE 1 - SCHEMATIC DIAGRAM OF A THIN-WALLED SUPPORTED-SHELL PARTICULATE-PACKED TITANIUM CONTAINER

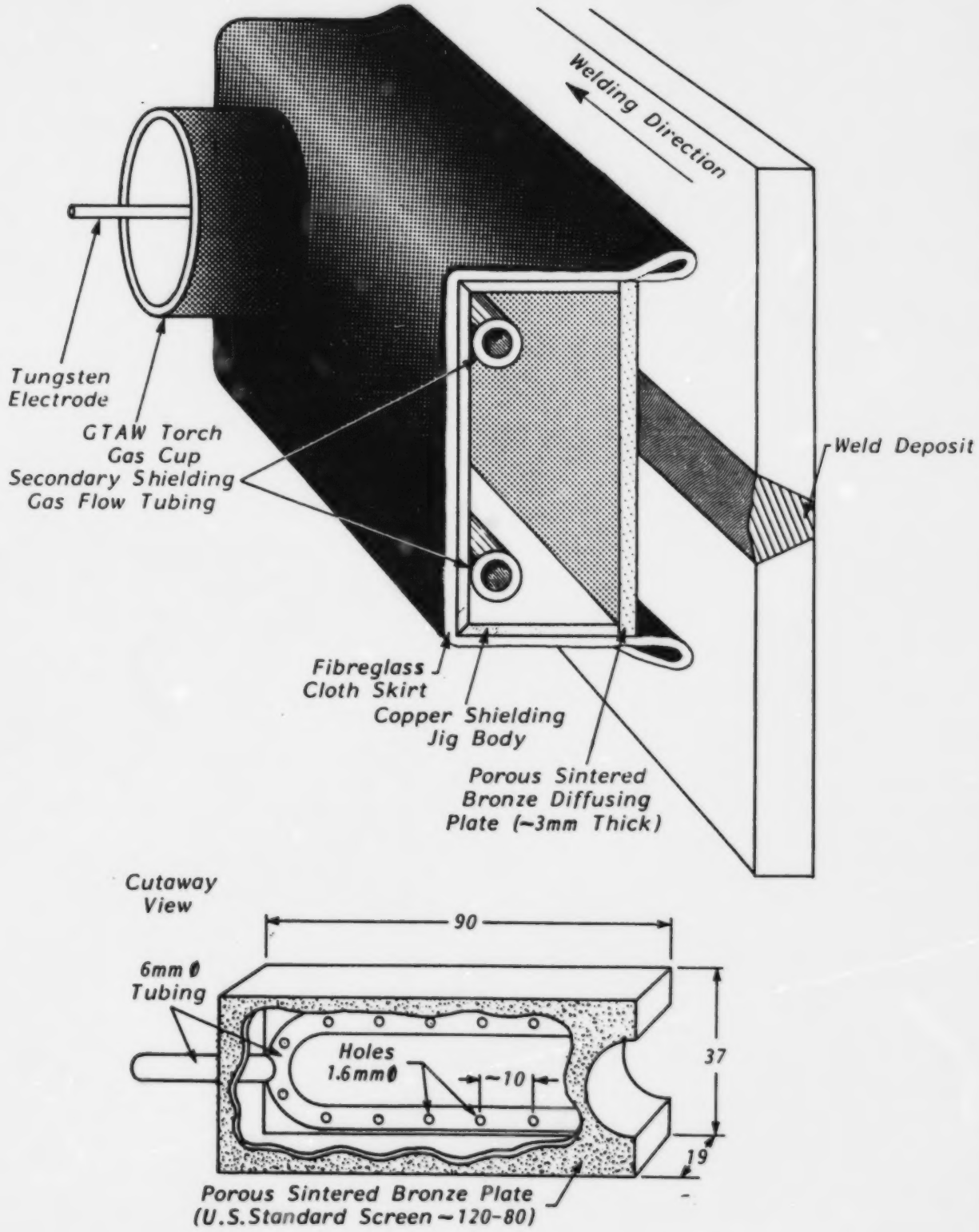


FIGURE 2

DESIGN OF TRAILING SHIELD FOR TITANIUM WELDING

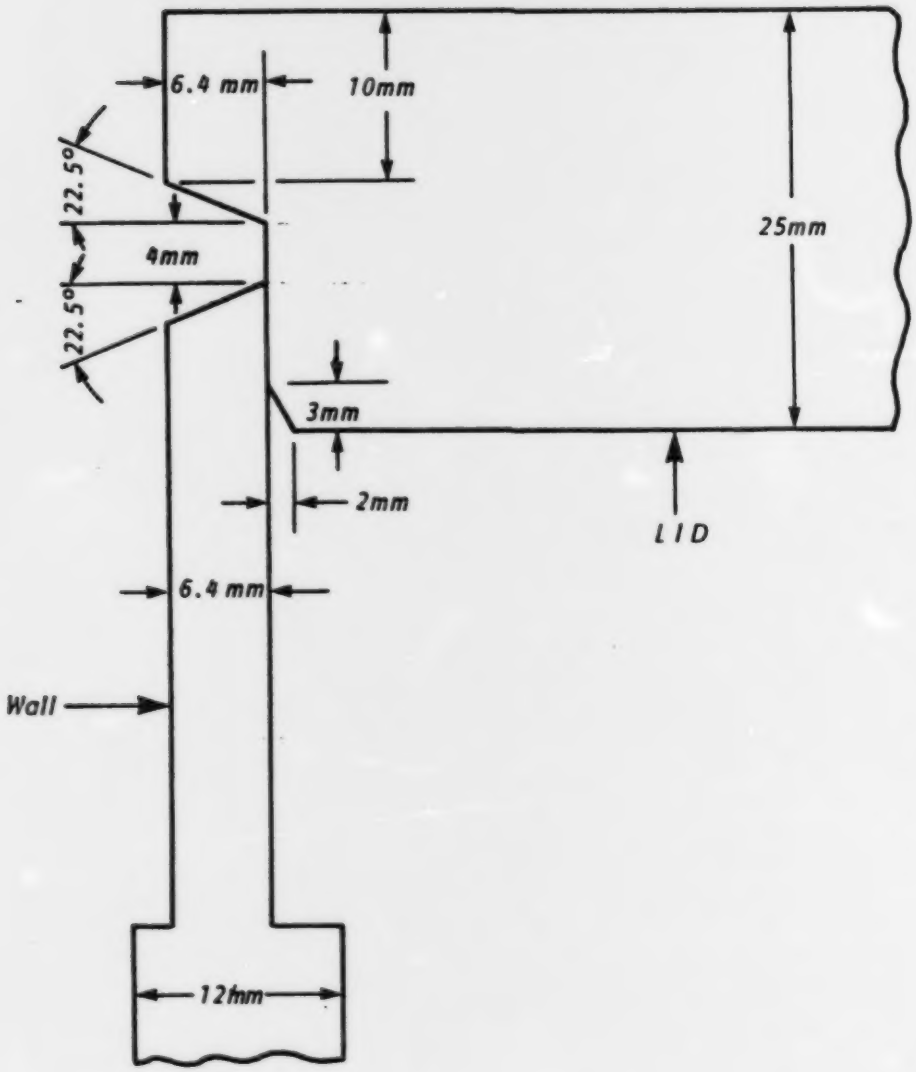
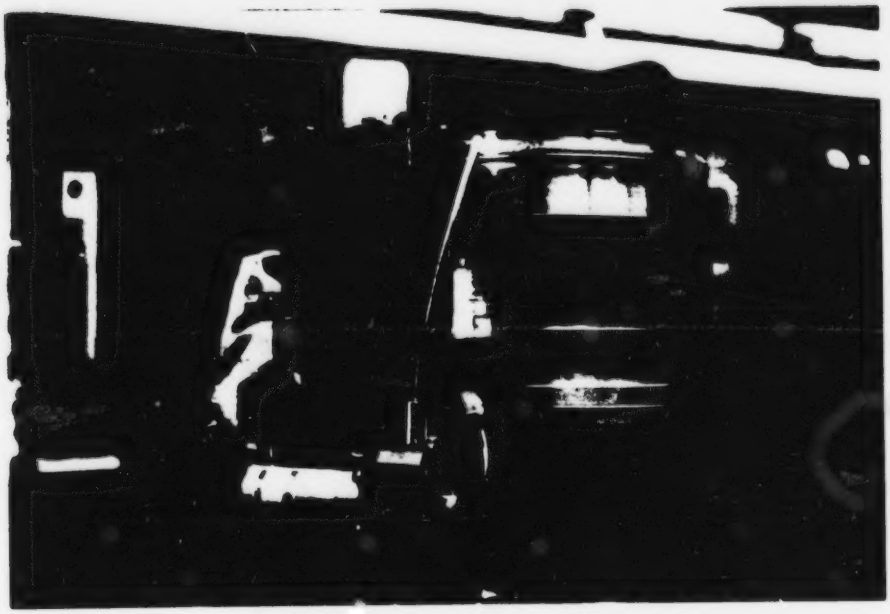
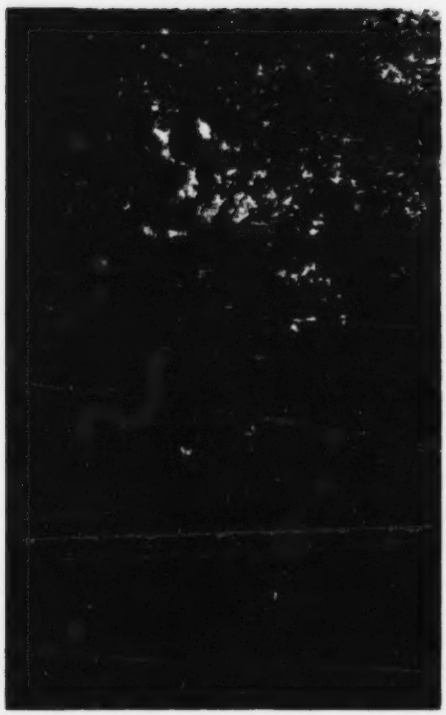


FIGURE 3
WELD JOINT DESIGN FOR THE TITANIUM PIPE MOCK-UP



a) Surface View



b) Cross Section
Mag 5X

FIGURE 4
SIMULATED LID WELD OF TITANIUM PIPE MOCK-UP

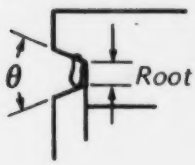
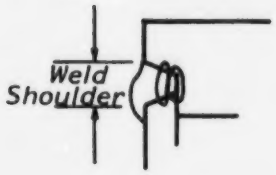
Problem	Possible Causes
 Lack of Root Penetration	θ too small root gap too small Insufficient current Excessive wire feed rate
Weld Metal Suck-Back	Excessive wire feed rate and current θ and root gap too small
Split Root Bead Formulation	θ too small Insufficient wire feed rate Electrode tip angle too small
Poor Root Bead Formation	Excessive misfit Poor placement of weld bead
Inadequate Inter-Bead Fusion	Excessive wire feed rate θ too small
Underfill	Insufficient wire feed rate Poor placement of weld bead
 Weld Pool Sag	Weld shoulder and θ too large Excessive wire feed rate Excessive current

FIGURE 5

COMMON CAUSES OF WELD DEFECTS IN TITANIUM GTA WELDS

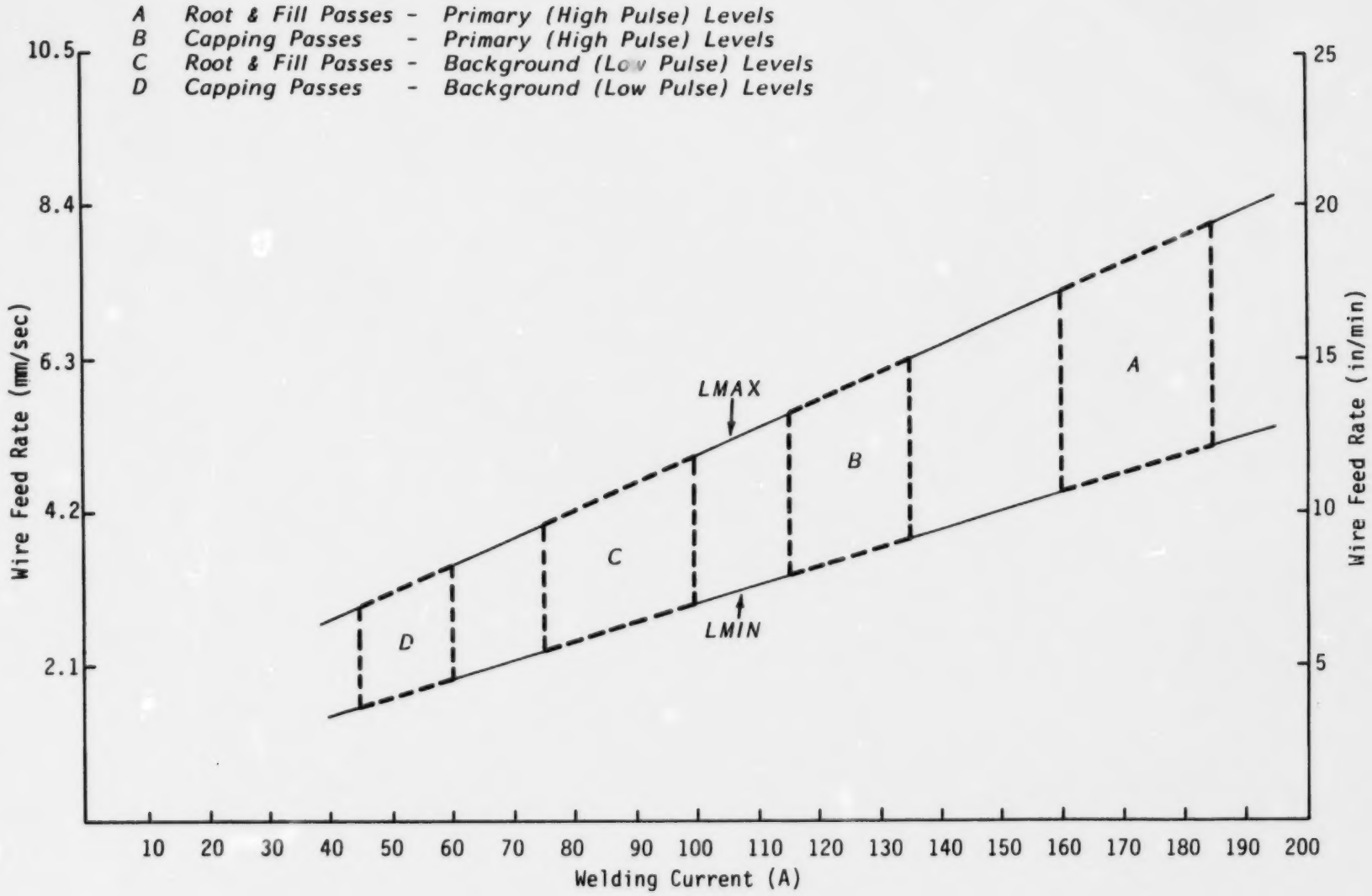


FIGURE 6

RECOMMENDED RANGE OF WELDING CURRENT AND WIRE FEED RATE FOR PULSED-CURRENT GTA WELDING OF TITANIUM IN THE 2G WELDING POSITION

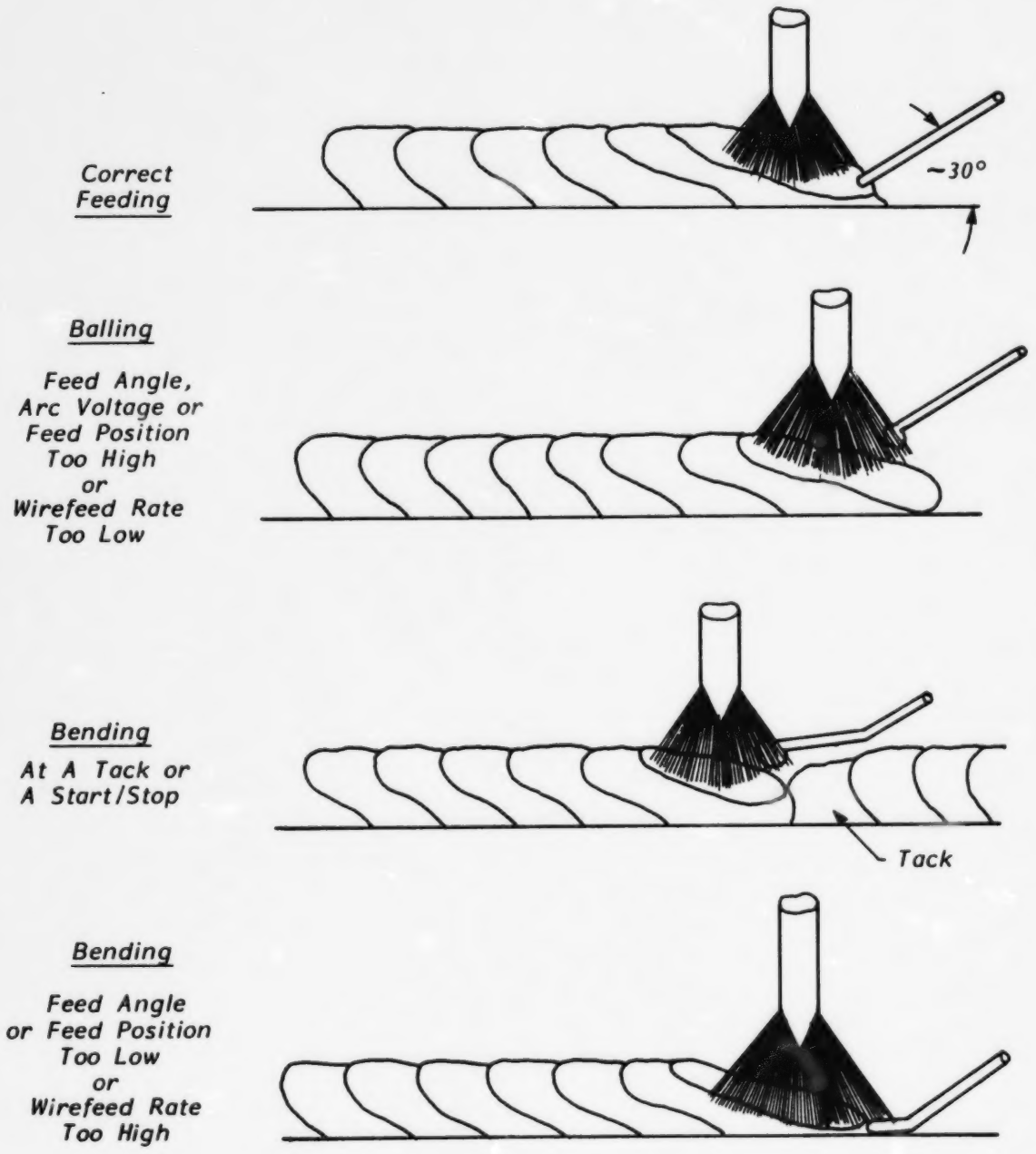


FIGURE 7
SCHEMATIC DIAGRAM OF WIRE FEED PROBLEMS

a) No Misfit

b) 0.7 mm Misfit

c) 1.4 mm Misfit

FIGURE 8

CROSS SECTIONS OF TITANIUM PLATE SAMPLES WELDED USING TEST 3 PARAMETERS
UNDER VARYING WELD JOINT FIT-UP CONDITIONS MAG 5.6 X

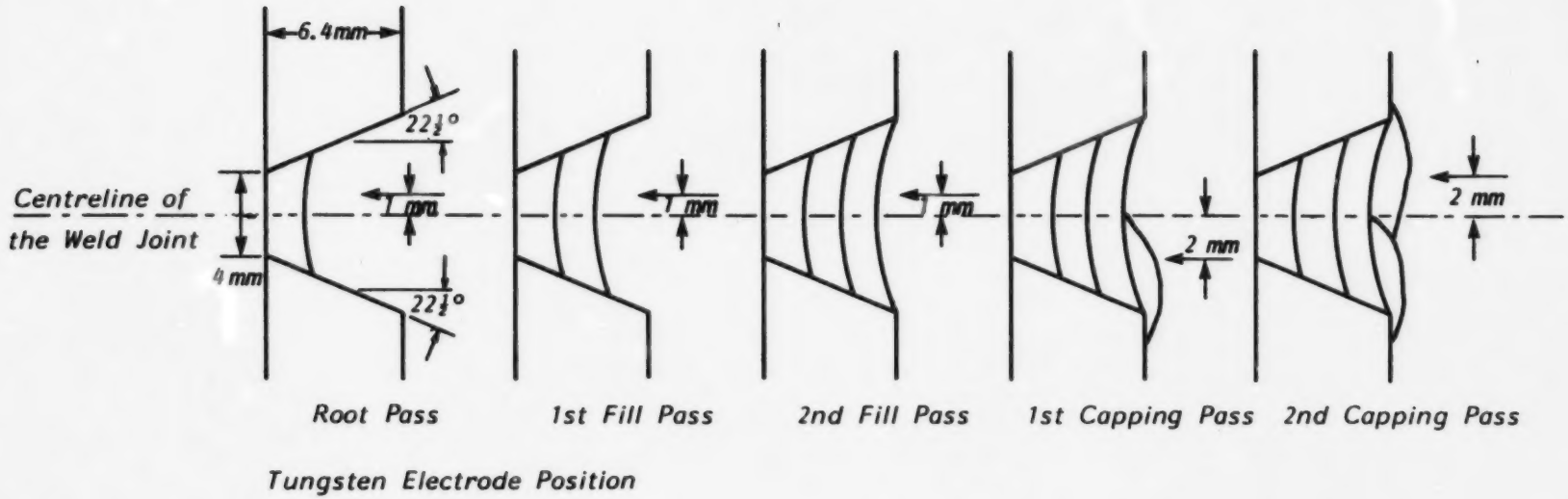


FIGURE 9

WELD BEAD PLACEMENT STRATEGY AND RECOMMENDED TUNGSTEN ELECTRODE POSITION FOR CLOSURE WELDING OF 6.4-mm-THICK TITANIUM CONTAINERS

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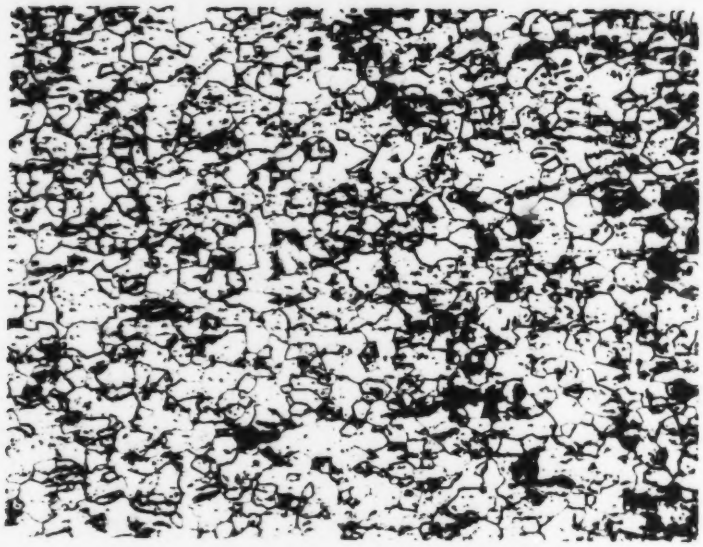
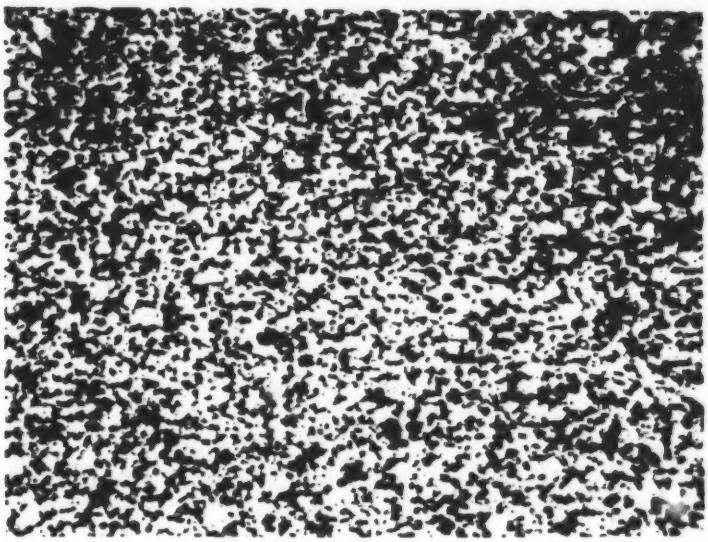


a) Base Metal

b) Weld Metal

FIGURE 10

MICROSTRUCTURE OF THE BASE METAL AND WELD METAL OF A TYPICAL GRADE 2 TITANIUM WELD MAG 100 X



a) Base Metal
Mag 100 X

b) Weld Metal
Mag 400 X

FIGURE 11

MICROSTRUCTURE OF THE BASE METAL AND WELD METAL OF A TYPICAL GRADE 12 TITANIUM WELD

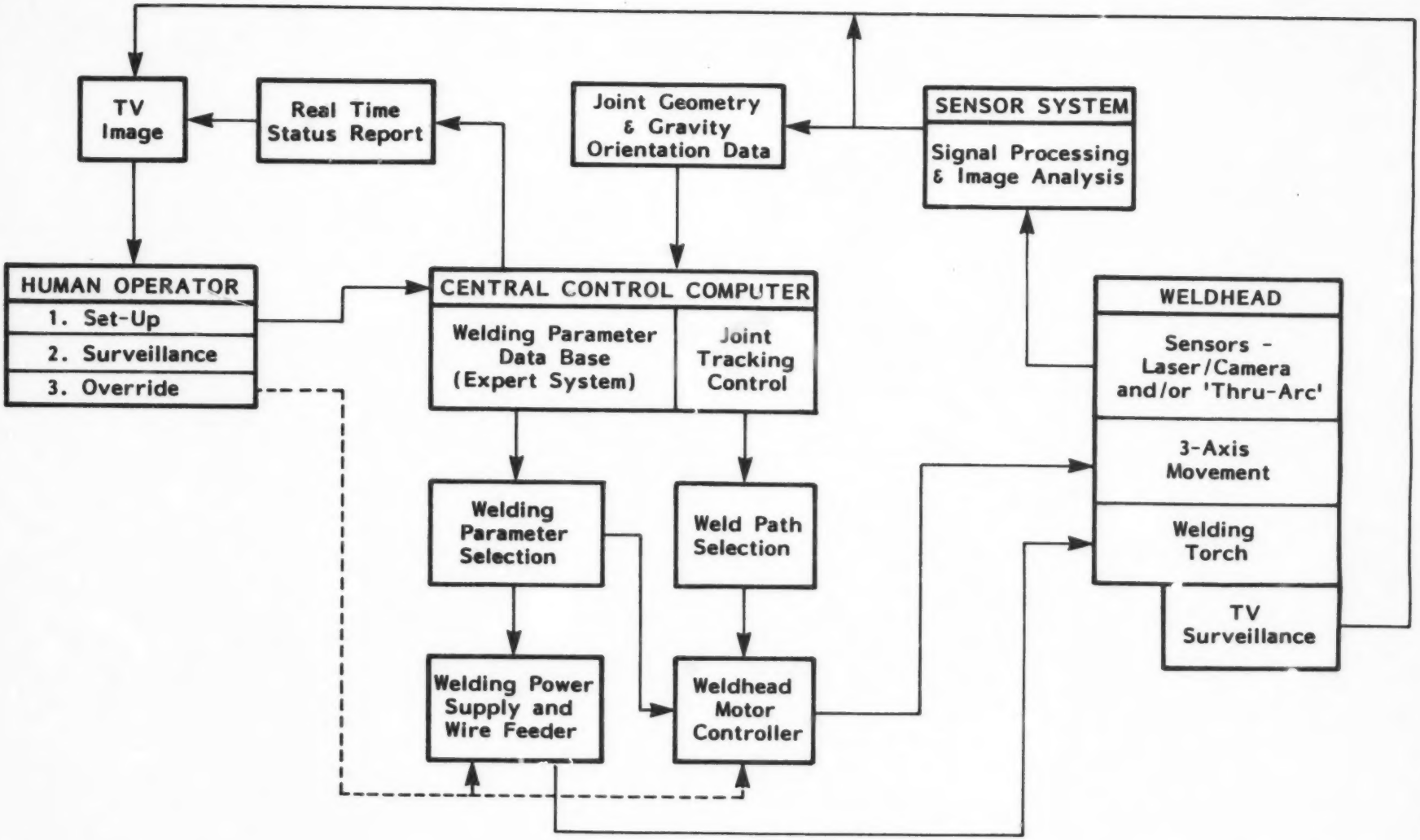


FIGURE 12

SCHEMATIC REPRESENTATION OF AN AUTOMATED ORBITAL WELDING SYSTEM

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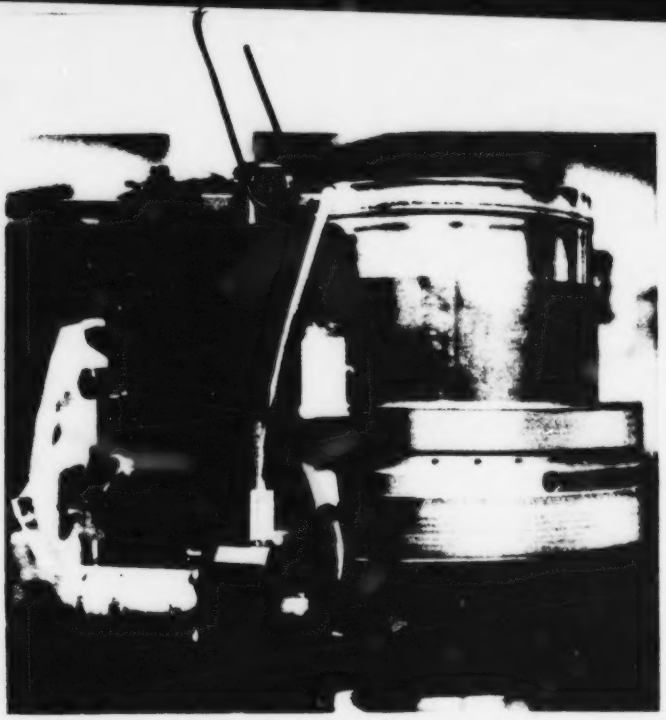

a) Surface View

b) Cross Section
Mag 5X

FIGURE 4
SIMULATED LID WELD OF TITANIUM PIPE MOCK-UP

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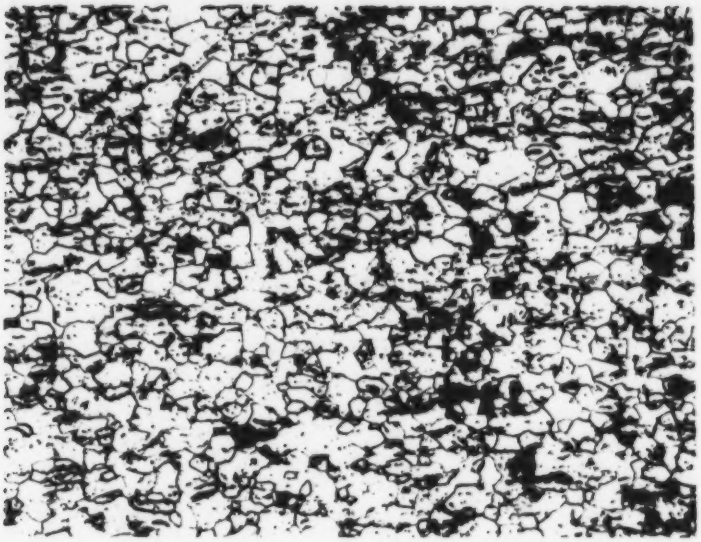


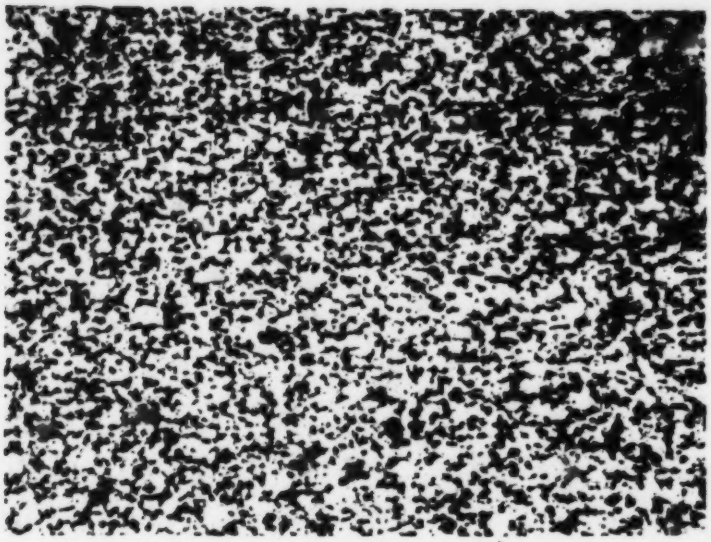
a) Base Metal

b) Weld Metal

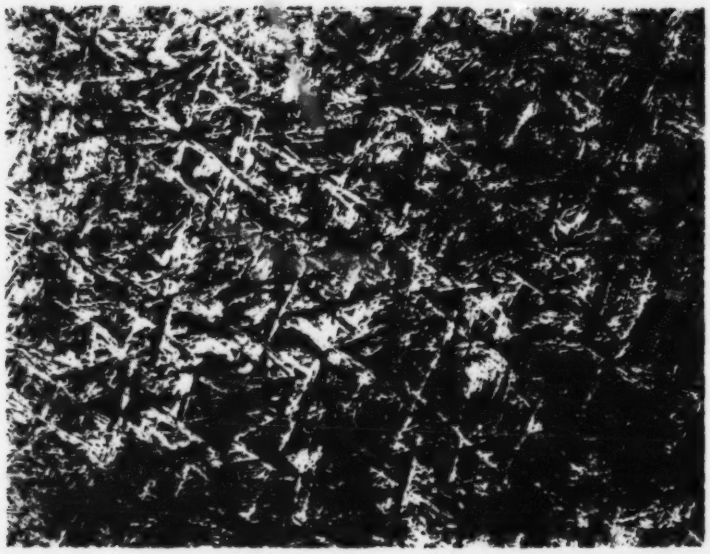
FIGURE 10

MICROSTRUCTURE OF THE BASE METAL AND
WELD METAL OF A TYPICAL GRADE 2
TITANIUM WELD MAG 100 X

173796-RD



a) Base Metal
Mag 100 X



b) Weld Metal
Mag 400 X

FIGURE 11

MICROSTRUCTURE OF THE BASE METAL AND WELD METAL OF A TYPICAL GRADE 12 TITANIUM WELD

173795-RD